NASA Technical Memorandum 104271

Simultaneous Measurement of Temperature and Strain Using Four Connecting Wires

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Edwards, California

1993

National Aeronautics and
Space Administration

Dryden Flight Research Facility
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ABSTRACT

This paper describes a new signal-conditioning technique for measuring strain and temperature which uses fewer connecting wires than conventional techniques. Simultaneous measurement of temperature and strain has been achieved by using thermocouple wire to connect strain gages to signal conditioning. This signal conditioning uses a new method for demultiplexing sampled analog signals and the Anderson current loop circuit. Theory is presented along with data to confirm that strain gage resistance change is sensed without appreciable error because of thermoelectric effects. Furthermore, temperature is sensed without appreciable error because of voltage drops caused by strain gage excitation current flowing through the gage resistance.

INTRODUCTION

Strain measurement during hot structural testing requires simultaneously measuring strain and temperature to correct for apparent strain output at the strain gage [1]. The traditional approach is to attach two independent sensors and signal-conditioning equipment for a strain gage and a thermocouple at the desired location. This paper shows that both sensors can be combined to form one sensor called the thermostrain gage. This combining process mixes the signals of both sensors.

In theory, appropriate signal processing separates and measures the voltages representing temperature and strain [2]. Such a system can use thermocouple wire to connect a strain gage to the data readout equipment. A new demultiplexer design accomplishes this goal through a combination of transducer wiring, alternating excitation, and signal processing to separate thermoelectric (thermocouple) and resistance change (strain gage) signals in such a manner that each signal contributes negligible contamination to the other. This design for signal separation is comprised of three main parts: the transducer wiring scheme, the Anderson current loop technique [2], and the analog demultiplexer design.

The key to system performance rests in the analog demultiplexer design. The demultiplexer separates the two signals which represent temperature and strain and which exist concurrently on the same pair of sense wires. The driving force behind the development of the new demultiplexer design was the need to acquire the temperature data at a strain gage location without using additional connecting wires. The demultiplexer design separates temperature and strain signals which originate at the strain gage location on a test specimen while using the same set of connecting wires. This paper describes a fully developed and laboratory-demonstrated signal demultiplexer design which implements Anderson's theory [2] with performance normally encountered in systems employing separate, independent strain and temperature sensors.

NOMENCLATURE

$A1$, $A2$, $A3$, $A4$	difference amplifiers
Cu	copper
e_{AB}	Seebeck voltage, V
emf	electromagnetic force, V
I_{ac}	alternating current level, mA
I_{dc}	direct current level, mA
INV	inverter amplifier

J	thermocouple junction
L	distance between two transducers
metal A, metal B,	metal types for thermocouples
metal C	metal type for strain gage
PLD	programmable logic device
R_I	initial gage resistance, Ω
R_{gage}	total gage resistance, Ω
R_{ref}	reference resistance, Ω
Rw	resistances of connecting wire, Ω
TC	thermocouple
V_{gage}	strain gage voltage, V
V_{out}	demultiplexer-sensed voltage, V
V_{outA}	demultiplexer A half-cycle voltage, V
V_{outB}	demultiplexer B half-cycle voltage, V
V_{ref}	reference resistor voltage, V
V_T	thermocouple voltage, V
ΔR	change in gage resistance, Ω
μe	microstrain
Ω	ohm

THERMOCOUPLE THEORY

The thermocouple (TC), a commonly used device for measuring temperatures [3], is used in many high-temperature applications because of its wide temperature range and ability to be optimized for use in various atmospheres. Each of the several types of TC's has its own set of properties. The process of selecting a specific type of TC for a particular application is beyond the scope of this paper.

A thermocouple is formed when two metal wires composed of different alloys are joined to form an electrical circuit. Figure 1 shows a thermocouple circuit. The joining of the two dissimilar metal wires completes an electrical circuit which sums the voltages produced when a temperature gradient exists along the different conductors. This voltage, called Seebeck voltage, is denoted as e_{AB}. For example, two wires composed of different metals, metal A and metal B, are joined at one end to create the thermocouple junction. The thermoelectric output of a TC is a function of temperature gradients along the TC wires. In a practical application, the output develops from temperature gradients between the thermocouple junction, where temperature is to be measured, and a temperature reference area, where the TC wire terminates.

ANDERSON CONSTANT CURRENT LOOP TECHNIQUE

The Anderson constant current loop technique is a new form of signal conditioning to observe remote resistance changes that significantly improves on the conventional Wheatstone bridge circuit [4]. This technique renders connecting wire resistance changes irrelevant while improving performance, linearity, and output efficiency.

As the name implies, the constant current loop technique is a constant current series circuit. This circuit has a constant current source which provides steady excitation for the strain gage transducers and other resistances in the loop in spite of changes in circuit resistance. The current is constant in all parts of the series circuit, regardless of connecting wire resistances. This consistency of the current holds true as long as the compliance range of the constant current source has not been exceeded. As in the classic Kelvin resistance measurement circuit, connecting wire resistances of the basic current loop can vary wildly and have no significant influence on the observed strain gage voltage, V_{gage}, as long as no appreciable current is conducted to the voltmeter which indicates V_{gage}. Figure 2 shows the Anderson constant current loop.

The following equations are derived from this loop:

$$V_{gage} = I_{dc}R_{gage} \tag{1}$$

where

$$R_{gage} = R_I + \Delta R \tag{2}$$

In equation (1), the I_{dc} is the direct current level. In equation (2), R_I represents the initial resistance of the strain gage under initial conditions of strain. The R_I can range from 60 to over 1000 Ω, depending on the particular strain gage being used. The ΔR represents the change in resistance because of strain which can vary from several milliohms to several ohms, proportional to the strain measured by the gage.

The Anderson constant current loop technique depends on the ability to perform precise analog voltage subtraction. The subtraction is performed on two voltage drops caused by the same constant loop current: a reference voltage drop, V_{ref}, and the gage voltage drop, V_{gage}. Both are sensed by a high-impedance voltmeter to achieve an essentially zero voltage drop along sense lines $Rw2$ and $Rw3$. The reference voltage is produced by a precision series resistance R_{ref} which approaches the value of R_I. In practice, R_I and R_{ref} differ slightly. This difference will result in a small output offset which is eliminated in data reduction. The analog subtraction calculates the difference in the voltage drops across R_{ref} and R_{gage}.

A conventional data acquisition channel for voltage has difficulty in reliably indicating a μV-level voltage change in the presence of much larger gage voltages of a few volts. By means of precise analog subtraction, the larger initial voltage produced by the excitation current flowing through R_I is precisely removed by subtracting from it the equivalent voltage drop across R_{ref}, leaving the much smaller voltage produced by ΔR to be measured directly.

When R_{ref} approaches the value of R_I,

$$V_{ref} = R_{ref} \times I_{dc} \tag{3}$$

$$V_{out} = V_{gage} - V_{ref} \tag{4}$$

Therefore,

$$V_{out} = I_{dc}\Delta R \tag{5}$$

While derived here in terms of electrical resistance and direct current excitation for simplicity, the Anderson current loop is a general measurement technique which can provide additional information when an alternating excitation current is used. In fact, alternating current excitation is necessary to combine (multiplex) strain and temperature signals in a manner which permits their later separation with an appropriate demultiplexer.

DEMULTIPLEXER DESIGN

The demultiplexer design was developed to enable simultaneous measurements of temperature and strain by using the same set of connecting wires at a given location on a test article. The conventional method of acquiring temperature and strain data at a specified single location requires placing a thermocouple and a strain gage in close proximity, so the thermocouple indicates the strain gage temperature. This method requires two signal-conditioning circuits and two sets of connecting wires for a total of six wires when using the Anderson constant current loop technique.

Figure 3 shows four connecting wires for strain and two for temperature. The distance between the two transducers, L, typically ranges from 0.762 (0.3) to approximately 1.27 cm (0.5 in.). With the new demultiplexer design, the two transducers are combined at the test article location through a unique wiring scheme (figure 4). The combination of the two transducers forms a new, single transducer called a thermostrain gage. This unique wiring combination uses one of the empirically derived laws of thermocouples, the Law of Intermediate Metals [3]. This law indicates that inserting the metal C element between metal A and metal B has no affect on the output voltage, V_{out}, regardless of the temperature of the metal C element if no temperature gradient exists along metal C (figure 4). The temperature of the connecting TC wire attached to electrical connection tabs of the conventional strain gage is, therefore, the sensed temperature. Heating and cooling caused by the Peltier effect average to zero with the reversing of excitation current [3]. The theory of operation and a practical design of the demultiplexer circuit are described next.

The Theory of Operation

Through the new signal-conditioning system, the voltage induced by the thermocouple effect at J4 and J5 and the voltage drop across the gage because of current I_{ac} are combined to comprise V_{out}. The V_{out} is measured by high-impedance voltmeters

within the demultiplexer signal conditioning. It actually represents two voltages: V_{outA} and V_{outB}. Figure 5 shows the alternating current waveform, I_{ac}, a reversing current of constant magnitude which alternates from I_{dc} to $-I_{dc}$. Each is derived from the same constant current regulator and switched to alternate in direction in successive half-cycles. During the first half of the cycle of I_{ac}, V_{outA} is produced, and the second half produces V_{outB}. Note that reversing the constant current I_{dc} has no affect on the voltage produced by the thermocouple effect or on the temperature of the gage.

In the A half of the cycle,

$$V_{outA} = I_{dc}(R_{gage}) + V_T \tag{6}$$

In the B half of the cycle,

$$V_{outB} = -I_{dc}(R_{gage}) + V_T \tag{7}$$

A Practical Design of the Demultiplexer Circuit

Figure 6 shows the circuit which causes the excitation reversal and the demultiplexer. The demultiplexer is divided into two sections: the sampling-switched capacitors and the signal manipulation.The current excitation section is comprised of a conventional constant current source and a set of current-reversing switches. The constant current source is typically set to 10 mA but can be adjusted to accommodate various gage resistances. The current-reversing operation (figure 5) is performed by four low on-resistance electronic switches. Synchronized timing of the current-reversing switches and the sampling-switched capacitors is accomplished by a digital programmable logic device (PLD). Details of the PLD programming and operation are beyond the scope of this paper.

Capacitors switched by components A and B transfer a voltage from a floating input to a ground-referenced output. Each switching component has two channels. Each component samples the same input and produces two copies of the same output. The positive and negative inputs for components A and B connect directly to the positive and negative sense-connecting wires to yield V_{outA} and V_{outB}, respectively. The switching of both components is synchronized by the PLD, so component A samples during the A half-cycle, and component B samples during the B half-cycle. Both components store V_{outA} and V_{outB}, respectively, across their output capacitors which are referenced to ground. The V_{outB} is then inverted by *A*3 to produce $-V_{outB}$. Components A and B track their respective half-cycle with neglectable interference because of switching effects.

The signal manipulation section is comprised of highly stable, integrated circuit instrumentation amplifiers which are used as difference amplifiers to perform precise analog subtraction. The difference amplifier, *A*1, is arranged with its output referenced to ground. The *A*1 subtracts $-V_{outB}$ produced by amplifier *A*3 from V_{outA} thereby calculating the thermoelectric output defined by equation (8):

$$\begin{aligned} V_{outA} - (-V_{outB}) &= [\,(I_{dc}(R_{gage}) + V_T) + (-I_{dc}(R_{gage}) + V_T)] \\ &= V_T + V_T \\ &= 2\,V_T \end{aligned} \tag{8}$$

Difference amplifier *A*2 subtracts V_{outB} from V_{outA} and yields the strain gage output defined by equation (9):

$$\begin{aligned} V_{outA} - V_{outB} &= [\,(I_{dc}(R_{gage}) + V_T) - (-I_{dc}(R_{gage}) + V_T)] \\ &= I_{dc}(R_{gage}) + I_{dc}(R_{gage}) \\ &= 2\,I_{dc}(R_{gage}) \end{aligned} \tag{9}$$

Equation (2) is used to subtract out the initial resistance R_I, where $R_{ref} = R_I$.

The voltage drop across R_{ref}, or V_{ref}, is amplified by a factor of 2 and inverted using *A*4. With *A*4's reference connected to ground, its output voltage serves to drive the reference terminal of *A*2. The connection of the output reference terminal of *A*2 to the $-2\,V_{ref}$ voltage level from *A*4 subtracts $2\,V_{ref}$ from $2\,I_{dc}(R_{gage})$. The output of *A*2 measured in reference to ground yields

$$2\,I_{dc}(\Delta R) + 2\,I_{dc}(R_I) - 2\,I_{dc}(R_{ref}) = 2\,I_{dc}(\Delta R) \tag{10}$$

which is the desired strain gage output. Note that connecting wire resistances and thermoelectric effects do not appear in this result. Note also that equations (8) and (10) contain a gain factor of 2 when compared with the standard Anderson current loop method. When compared with conventional Wheatstone signal conditioning, both equations contain a gain factor of 4 [4].

LABORATORY DEMONSTRATION

A practical circuit based on figure 6 was designed, constructed, and tested. A solderless prototyping breadboard was used to verify circuit operation and to collect the data for a functional check. The two transducers, the thermocouple, the strain gage, and the wiring scheme were simulated using a digital thermocouple calibrator and a resistor decade box, respectively. This approach ensured that resistance and thermoelectric effects were independently controlled. As a result, apparent strain was not a source of error in verifying the system operation.

Two tests in which each transducer was varied independently were performed. In the first test, the thermocouple simulator output was held constant, and the strain-simulating decade box was varied from 5 to -5 Ω with an initial resistance of 120 Ω, and the I_{dc} was set to 10 mA. This test was performed four times with consistent results. Figure 7 shows the results scaled to 20,833 µstrain, assuming a gage factor of 2. Gage resistance variations simulated by the decade box have no observable affect on the temperature output as predicted by equation (8). Note that the full temperature scale in the figure is equivalent to approximately 0.5 °C (1 °F), using type K thermocouple wire. In addition, the temperature measurement noise floor is approximately 0.1 °C (0.20 °F).

In the second set of four tests, the gage resistance was held constant ($\Delta R = 0$). The thermocouple simulator was set as follows: 0, 14, 50, 14, and 0 mV. These simulation settings represent a temperature variation from 0 to 1260 °C (32 to 2300 °F) for type K thermocouple wire. Figure 8 shows typical test results. The figure shows that gross variation of temperature has no observable affect on the strain output, as predicted by equation (10). The strain noise floor is approximately 1 µin/in. from peak to peak.

CONCLUSION

Simultaneous measurement of temperature and strain has been achieved by using thermocouple wire to connect strain gages to signal conditioning. This approach uses a new method for demultiplexing sampled analog signals and the Anderson current loop technique. Theory is confirmed by data to demonstrate that strain gage resistance change is sensed without appreciable error because of thermoelectric effects. Furthermore, temperature is sensed without appreciable error because of voltage drops caused by strain gage excitation current flowing through the gage resistance and connecting wires.

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1. De Angelis, V. Michael and Fields, Roger A., *Techniques for Hot Structures Testing,* NASA TM-101727, 1990.
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4. Wheatstone, Charles, "An Account of Several New Instruments and Processes for Determining the Constants of a Voltaic Circuit," *Philosophical Transactions of the Royal Society of London,* vol. 133, 1843, pp. 303–329.

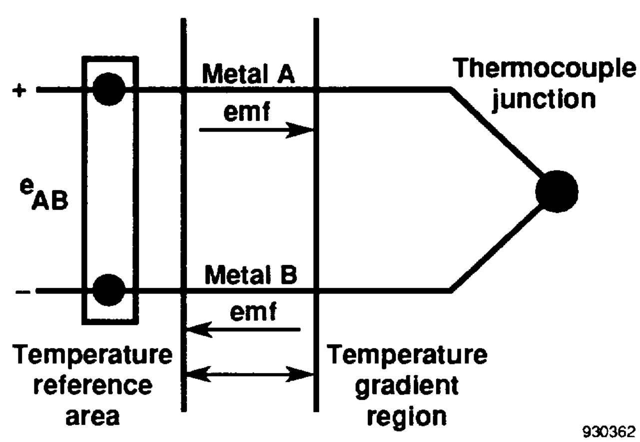

Figure 1. Thermocouple circuit.

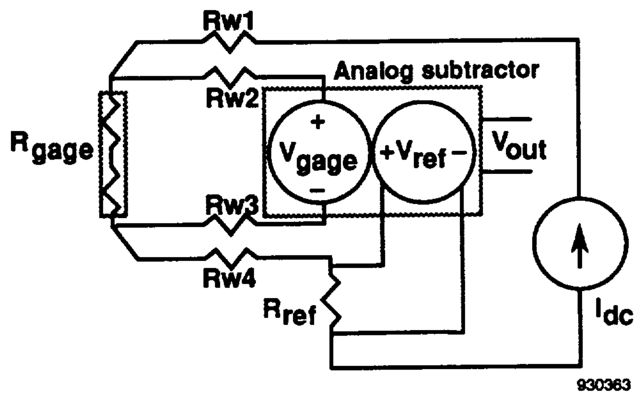

Figure 2. Anderson constant current loop.

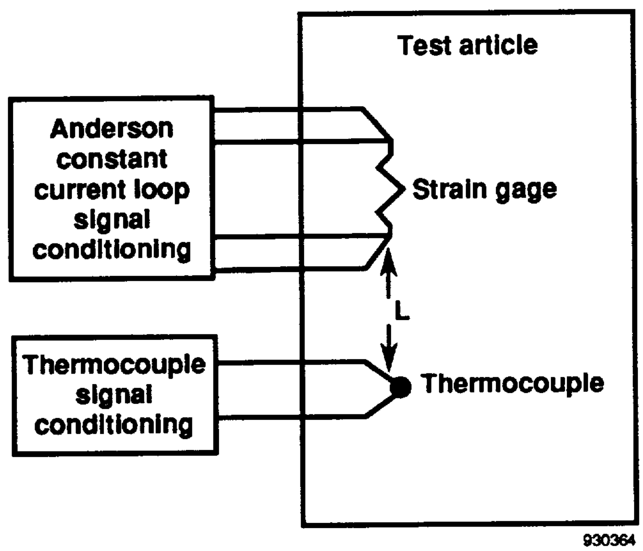

Figure 3. Conventional installation of a strain gage and a thermocouple on test article.

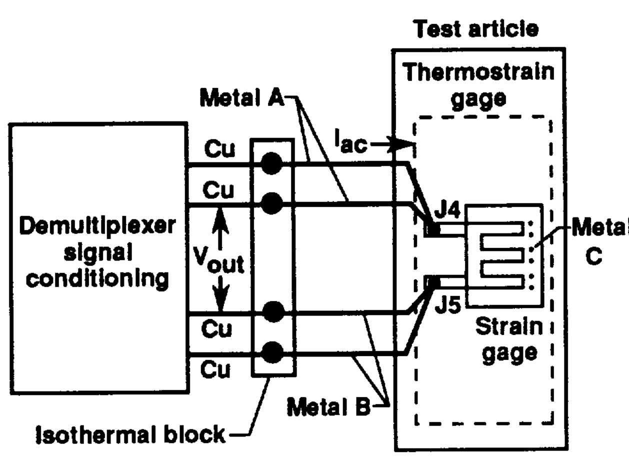

Figure 4. Demultiplexer wiring scheme.

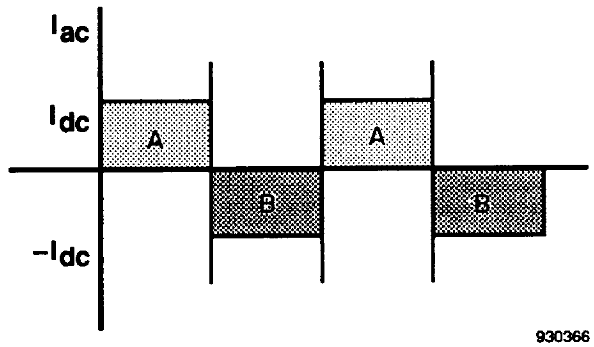

Figure 5. Alternating current waveform.

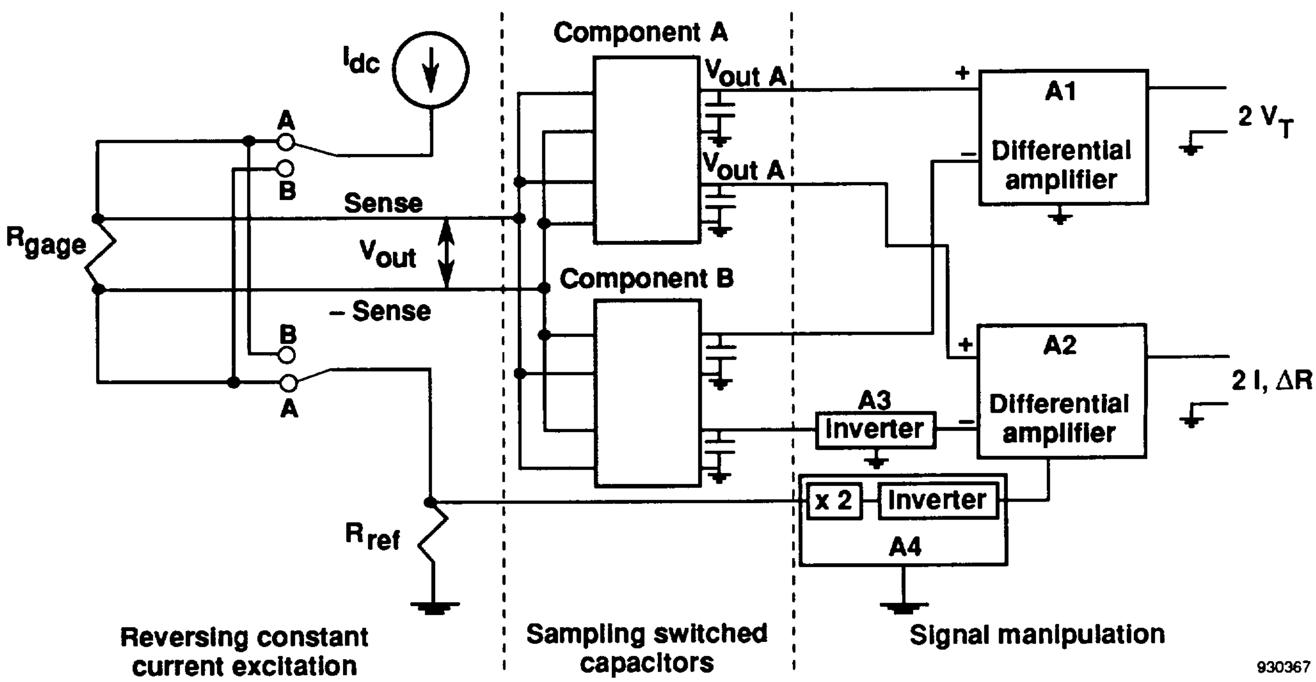

Figure 6. Demultiplexer circuit.

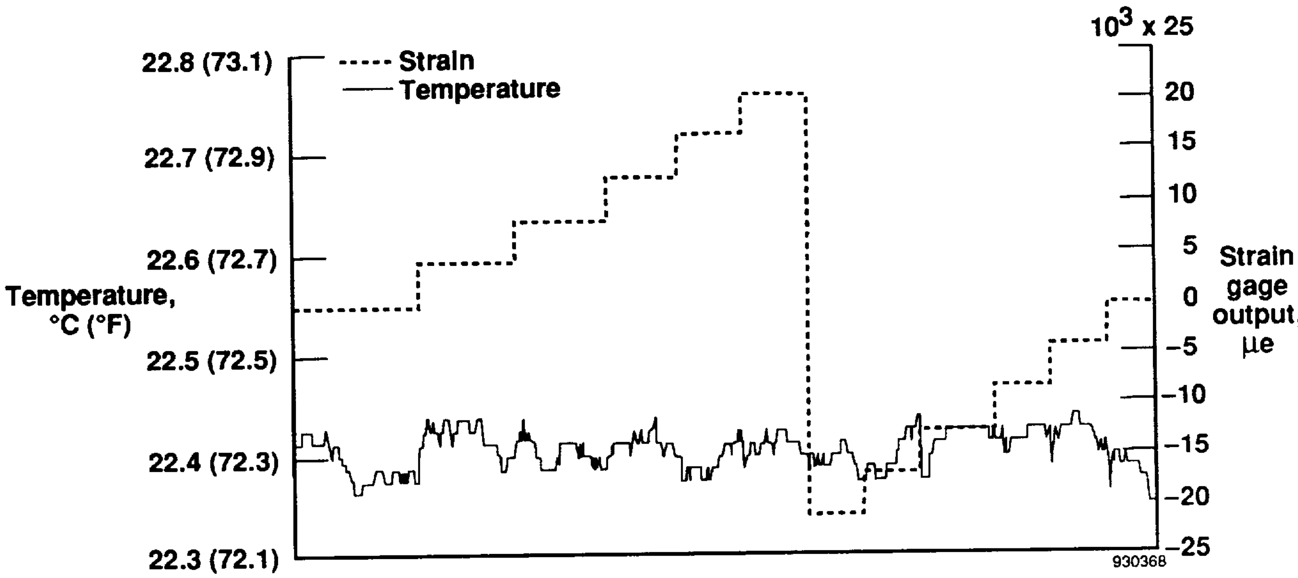

Figure 7. Simulated strain with constant temperature.

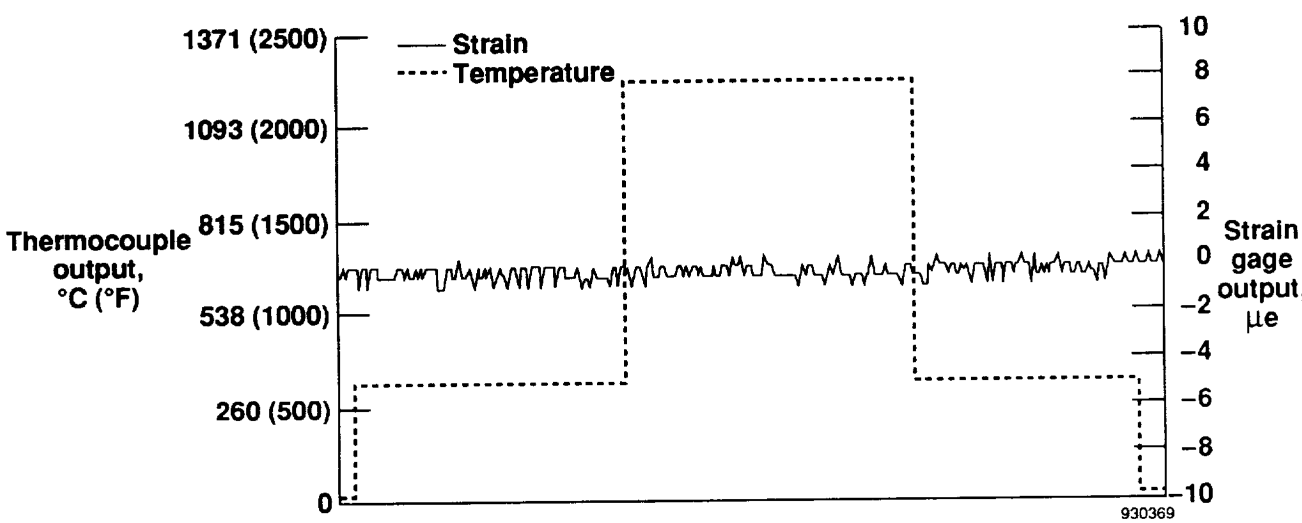

Figure 8. Simulated temperature with constant strain.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1993	Technical Memorandum

4. TITLE AND SUBTITLE
Simultaneous Measurement of Temperature and Strain Using Four Connecting Wires

5. FUNDING NUMBERS
WU 505-70-63

6. AUTHOR(S)
Allen R. Parker, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Dryden Flight Research Facility
P.O. Box 273
Edwards, California 93523-0273

8. PERFORMING ORGANIZATION REPORT NUMBER
H-1945

9. SPONSORING/MONOTORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-104271

11. SUPPLEMENTARY NOTES
Presented at SEM Fall Conference and Exhibit—on Structural Testing Technology at High Temperature-II, Ojai, California, November 8, 1993.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 35

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS
Bridge circuits, Instrumentation, Signal demultiplexer, Simultaneous measurement, Strain gage instruments, Thermocouple, Transducers

15. NUMBER OF PAGES
12

16. PRICE CODE
AO3

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Available from the NASA Center for SeroSpacer Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090; (301) 621-0390.

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102